Research on Phase-Locked Loop Control and Its Application

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***Abstract*—In view of the importance of the phase locked loop (PLL) in the control of inverter, the SOGI-QSG based single phase PLL is taken as the research object, and its operating principle and control performance are analyzed in detail, which provides reference for the design of the phase locked loop. Aiming at the PLL based islanding detection methods have adverse effects on the power supply quality of the distributed generation (DG), this paper proposes a PLL based passive islanding detection method, which adds time delay in PLL control and can effectively improve the power quality of the DG supply, the simulation results verify the effectiveness of the proposed islanding detection method.**

Keywords*—component; formatting; style; styling; insert (key words)

I. INTRODUCTION

In inverter control of distributed generation (DG) system, it is necessary to obtain the phase information of grid voltage in order to achieve the control of the active power and reactive power, which requires the use of phase locked loop (PLL) to lock the grid voltage phase. As one of the core technology of inverter control, the performance of PLL has a direct impact on the grid-connected control performance of inverter. PLL has various types, according to the implementation way, it can be divided into hardware PLL and software PLL; by applications it can be divided into three-phase PLL and single-phase PLL; and from the control structure to classify, includes open-loop PLL and closed-loop PLL[1]~[3].

In DG system, in addition to be used in phase lock, the PLL can also be used in islanding detection. In the relevant reports, the researchers added perturbation signal to the PLL of inverter, so that after disconnecting the grid the voltage amplitude or frequency of point of common couple (PCC) shifted more than a threshold to detect the islanding. The disadvantage of this method is that the disturbance signal is added to PLL, which reduces the power supply quality of DG system. In order to guarantee the power supply quality, on the basis of study of structure and control performance of the PLL, this paper proposes a PLL based islanding detection method without the need of adding the disturbance signal. The effectiveness of the proposed method is verified by Matlab simulation.

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II. RESEARCH ON THE OPERATING PRINCIPLE AND CONTROL PERFORMANCE OF PLL

A. Operating Principle of PLL

In the operation of grid-connected inverter, the PLL dynamic obtain phase, frequency and amplitude information of the grid voltage to achieve the purpose of synchronous control in order to achieve the inverter connected to the grid. figure 1 is the operating principle diagram of PLL, where U is the actual voltage vector, U_{PLL} is the output voltage vector of PLL. With U_{PLL} as the d-axis, the q-axis component of U reflects the size of phase lock error. By controlling so that u_{q}, the q-axis component of U, is 0, so the output voltage phase of PLL is the same as that of actual voltage, that is $\hat{\theta}=\theta$, then precise phase lock can be achieved.

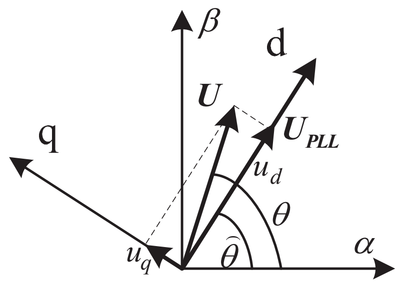

Fig. 1. the operating principle diagram of PLL

B. Control Performance Analysis of PLL

For convenience, a single-phase PLL is chosen to analyze the control performance. Since in single-phase system the voltage signal exists only one degree of freedom, the coordinate transformation can not be directly carried out, we need to construct a virtual variable to form quadrature signals with two degrees of freedom. Therefore, an quadrature signal generator (QSG) based on second-order generalized integrator (SOGI) is used, which is called SOGI-QSG. With this type of QSG, a signal with the same phase as the original signal and its 90° phase difference quadrature signal will be generated, at the same time, it can eliminate the harmonic components of the original signal, so that it can accurately obtain the grid voltage information in an unsatisfactory grid condition[4] [5].

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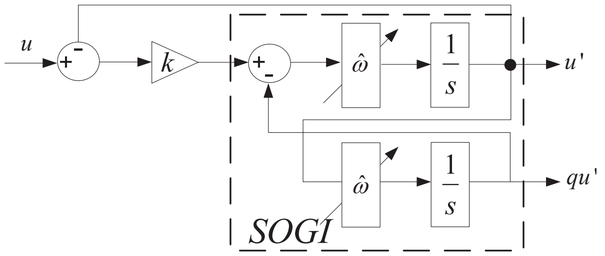


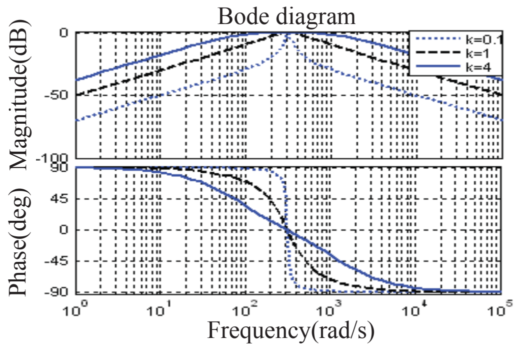
Fig. 2. the schematic diagram of SOGI-QSG

Figure 2 is the schematic diagram of SOGI-QSG, the transfer function of the two output signals relative to the input signal is

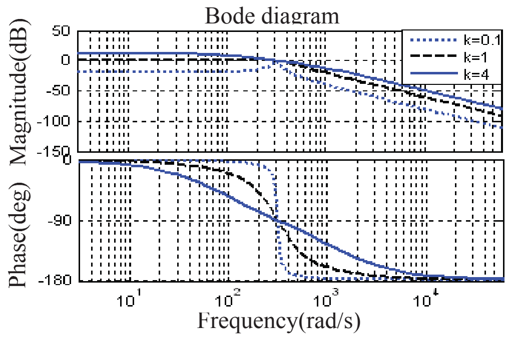
$$D(s)=\frac{u'(s)}{u(s)}=\frac{k\hat{\omega}s}{s^2+k\hat{\omega}s+\hat{\omega}^2} \tag{1}$$

$$Q(s)=\frac{qu'(s)}{u(s)}=\frac{k\hat{\omega}^2}{s^2+k\hat{\omega}s+\hat{\omega}^2} \tag{2}$$

For different values of the gain k, the Bode diagram of the above transfer function is shown in figure 3.



(a) the Bode diagram of D(s)



(b) the Bode diagram of Q(s)

Fig. 3. the Bode diagram of SOGI-QSG

According to figure 3, we can see that the smaller the k value, the better the filtering effect, but also the smaller the system bandwidth, and the response speed will be slower. Considering the tradeoff between the filter effect and the response speed, it is appropriate to select $k=\sqrt{2}$.

If the sinusoidal signal u is represented as a vector $\overline{u}$, by the formula (1), (2) to obtain

$$\overline{u'}=\overline{D}\overline{u}\begin{cases}\left|\overline{D}\right|=\dfrac{k\hat{\omega}\omega}{\sqrt{(k\hat{\omega}\omega)^2+(\omega^2-\hat{\omega}^2)^2}}\\ \angle\overline{D}=\tan^{-1}\left(\dfrac{\hat{\omega}^2-\omega^2}{k\hat{\omega}\omega}\right)\end{cases} \tag{3}$$

$$\overline{qu'}=\overline{Q}\overline{u}\begin{cases}\left|\overline{Q}\right|=\dfrac{\hat{\omega}}{\omega}\left|\overline{D}\right|\\ \angle\overline{Q}=\angle\overline{D}-\dfrac{\pi}{2}\end{cases} \tag{4}$$

By the formula (3) and (4), it can be known that qu' is always lagging behind u' 90°, and it has nothing to do with k, $\hat{\omega}$ and ω. Since the SOGI-QSG has frequency-selective property, even if the input signal contains harmonic component, the two quadrature output signals don't contain harmonic component. Due to the limited bandwidth of SOGI-QSG, the resonant frequency $\hat{\omega}$ of SOGI should be adjusted adaptively so that it is equal to the input signal frequency ω.

On the basis of SOGI-QSG, the schematic diagram of PLL is shown in figure 4. Firstly, the SOGI-QSG generates two quadrature output signals from the input voltage u, the phase of output voltage u' is consistent with the phase of input voltage u, another output qu' lags the input 90°; secondly, the Park transform is performed on the two quadrature output signals to obtain the q-axis component u_q of the input voltage vector; finally, the closed-loop control of the q-axis component is carried out, and the frequency and phase information of the input voltage u is obtained. In figure 4, ω^* is the feedforward value of frequency, usually it is the voltage rated frequency and is used as the quiescent operating point of the system, which allows the closed-loop system of PLL to work in a smaller linear range to benefit to PI parameter design.

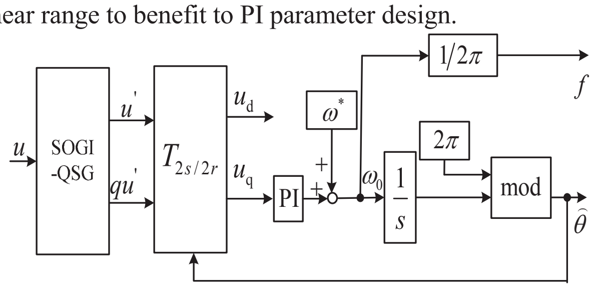


Fig. 4. the schematic diagram of PLL

Assuming that the initial phase of the input voltage is 0, it can be expressed as

$$u=U\cos\omega t=U\cos\theta \tag{5}$$

If the resonant frequency of SOGI is equal to that of the input signal, the output signal expressions of SOGI-QSG are

$$\begin{aligned}u'&=U\cos\omega t\\ qu'&=U\sin\omega t\end{aligned} \tag{6}$$

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After the Park transform of the two output signals, it can be obtained that

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\hat{\theta} & \sin\hat{\theta} \\ -\sin\hat{\theta} & \cos\hat{\theta} \end{bmatrix} \begin{bmatrix} u' \\ qu' \end{bmatrix} = \begin{bmatrix} U\cos(\theta-\hat{\theta}) \\ U\sin(\theta-\hat{\theta}) \end{bmatrix} \quad (7)$$

When $(\theta-\hat{\theta})$ is small enough, $\sin(\theta-\hat{\theta})\approx(\theta-\hat{\theta})$, the q-axis component of the input voltage vector is

$$u_q = U(\theta-\hat{\theta}) \quad (8)$$

Thus the control structure of PLL can be obtained as shown in figure 5, and the transfer function of the PI control loop is

$$K_f(s) = K_p + \frac{K_i}{s} \quad (9)$$

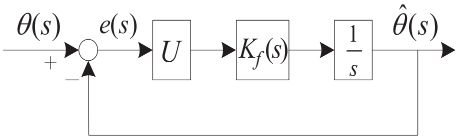

Fig. 5. the control structure of PLL

According to figure 5, the closed loop transfer function of the PLL is

$$\frac{\hat{\theta}(s)}{\theta(s)} = \frac{2\xi\omega_n s+\omega_n^2}{s^2+2\xi\omega_n s+\omega_n^2} \quad (10)$$

Where $\omega_n=\sqrt{UK_i}$, $\xi=0.5K_p\sqrt{U/K_i}$.

Assuming that at the moment of t=0, the phase jump of input voltage is $\Delta\varphi$, then

$$\lim_{t\to\infty} e(t) = \lim_{s\to 0}\frac{\Delta\varphi s^2}{s^2+2\xi\omega_n s+\omega_n^2} = 0 \quad (11)$$

Assuming that at the moment of t=0, the frequency skipping of input voltage is $\Delta\omega$, then

$$\lim_{t\to\infty} e(t) = \lim_{s\to 0}\frac{\Delta\omega s}{s^2+2\xi\omega_n s+\omega_n^2} = 0 \quad (12)$$

The formula (11) and (12) show that after the phase or frequency of the input voltage is changed, the PLL can implement the phase detection without static error, and the response speed depends on the characteristic frequency ω_n.

III. THE APPLICATION OF PLL IN ISLANDING DETECTION

A. Overview of PLL Based Islanding Detection Method

When the main power grid is disconnected by reason of malfunction, maintenance and other reasons, DG system continues to supply the load, the formed isolated power system is called islanding. Islanding detection is a necessary function of grid-connected inverter, The detection methods of islanding are divided into two categories: passive and active methods. Active islanding detection method need to add disturbance in the control signal of inverter, while passive detection is not required to add disturbance to the control signal.

The islanding detection application of PLL has been reported in some literatures. Literature [6] added a small sinusoidal perturbation in the output phase angle of PLL, its effect was equivalent to a feedback signal associated with the grid impedance was added in the voltage of PCC, then calculated the magnitude of the feedback signal by quadrature transformation, if the magnitude continuously exceeded the threshold more than 0.2 seconds, it could be determined that the islanding occurred. Literature [7] used PLL control with droop characteristic, and added disturbance to the droop component of PLL output frequency signal, so that in islanding state the frequency shifted continuously and exceeded the detection threshold thus the islanding was detected. In literature [8] and [9], a small signal model of three phase PLL based on DQ transformation was firstly established to analysis the PLL small signal stability of islanding state, on this basis, added a disturbance in PLL structure, which made the PLL control under the condition of islanding was unstable, and the frequency could continuously shift to exceed the threshold to detect the islanding.

B. Research on the PLL Based Passive Islanding Detection Method

The aforementioned PLL based islanding detection methods are all active methods, Their common shortcoming is that the added disturbance signal reduces the power supply quality of DG system. In view of the shortcoming of these detection methods, a PLL based passive islanding detection method is proposed in this paper. According to the proposed method, the PLL control remains stable in grid-connected state but loses its stability in islanding state due to the change of circuit structure in these two states. Therefore, after the grid disconnection the frequency of PCC voltage can be continued to offset and exceed the threshold to achieve the purpose of islanding detection. Due to there is no disturbance in the PLL control, the power supply quality of DG system will not be affected.

The DG system structure with PLL based islanding detection is shown in figure 6. In this figure, the PLL structure is in the dotted line box, wherein PD is a phase detector, LF is a loop filter, and VCO is a voltage controlled oscillator. Phase detector compares the phase difference between the PCC voltage and the PLL output signal to generate an error voltage corresponding to the phase difference of the two signals; the AC component of the error voltage is filtered out by the loop filter, and the output signal of loop filter controls the voltage controlled oscillator to output a sinusoidal signal, which is synchronized with the PCC voltage, and the phase locked function is achieved. Different from conventional PLL, in the PLL structure of figure 6, a time delay is added in feedback branch. When the grid is not disconnected, the PCC voltage is limited by the grid voltage, and the frequency of PLL output signal is stable; after the grid is disconnected, the PCC voltage depends on the inverter output current and the impedance of the local load, the addition of time delay in PLL makes the phase margin of the inverter control loop reduce even become negative, so the DG system loses its stability, the frequency of

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PLL output signal continued to change and beyond the threshold to detect the islanding.

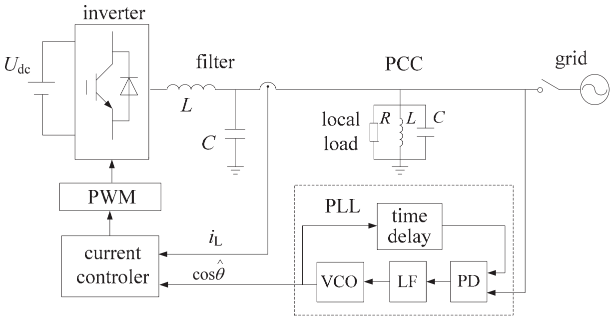

Fig. 6. The DG system structure with PLL based islanding detection

To verify the effectiveness of the proposed PLL based passive islanding detection method, Matlab simulation was carried out. The simulation model was composed of two single phase grid-connected inverters to constitute the DG system, as shown in figure 7. System configuration parameters were as follows: the grid was 220V/50Hz single-phase AC; Two inverters took unity power factor current control strategy, the output power were all 500W and match the power of local parallel RLC load, load quality factor $Q_f = 2.5$.

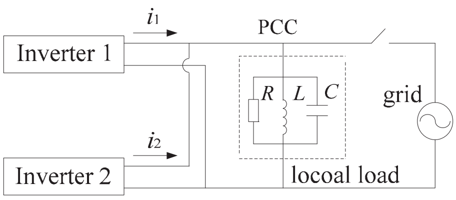

Fig. 7. the DG system with two sets of grid connected inverters

Figure 8 was the islanding detection simulation waveform. As could be seen from figure 8, at time of 0.1 seconds after the grid was disconnected, grid current was reduced to zero. The inverter output currents and PCC voltage reduced to 0 at about 0.33 seconds, indicating that the islanding had been successfully detected and the islanding protection had been implemented, the detecting time was 0.33-0.1=0.23 seconds, which could meet the requirements of the national standard for islanding detection time[10].

IV. CONCLUSION

In DG system, PLL is a key to realize inverter grid-connected control, the PLL control performance has great impact on system stability, and it also determines whether or not the inverter can connect to the grid successfully. In this paper, the operating principle and control performance of SOGI-QSG based single phase PLL are analyzed in detail to provide reference for the PLL design. In addition, the PLL can also be used in inverter islanding detection. At present, the PLL based islanding detection methods adopt active detection mode, which have adverse effects on the power supply quality of DG system. For this reason, based on the study of the structure and control performance of PLL, this paper proposed a PLL based passive islanding detection method, which use time delay instead of adding disturbance in PLL control , so the power supply quality of DG system can be improved.

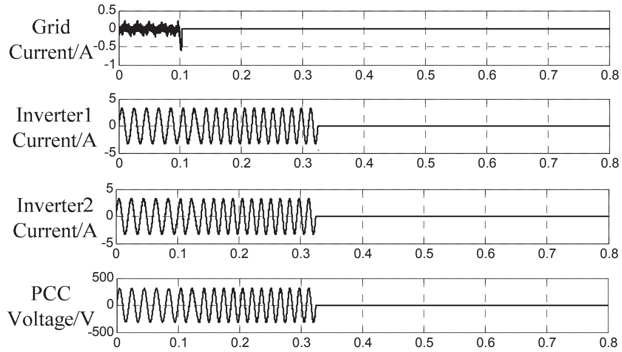

Fig. 8. islanding detection simulation waveform adopting PLL based passive islanding detection method

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